NITROGEN FIXATION IN FOREST SOILS OF THE INLAND NORTHWEST

Martin F. Jurgensen
Jonalea R. Tonn
Russell T. Graham
Alan E. Harvey
Kathleen Geier-Hayes

ABSTRACT

Significant amounts of soil nitrogen (N) are lost from the soil during timber harvesting and related activities. Symbiotic N-fixing plants have the potential to replace much of these N losses on many sites in the Inland Northwest, especially during early stand development. However, many of these plants are site specific and can cause competition problems during stand establishment. Much more information is needed on the successional roles of N-fixing plants in Inland Northwest forests. Nonsymbiotic N fixation in forest soils of this region is low, but is an important source of N on sites where N-fixing plants are lacking or of low frequency. Appreciable amounts of N can be added to the soil by nonsymbiotic N fixation over long stand rotation ages typical for this region. Silvicultural systems need to be developed that minimize soil N losses and maintain the biological N fixation potential of the site.

INTRODUCTION

Timber harvesting and subsequent site preparation methods used in western forests can cause significant reductions in the levels of nitrogen (N) in forest soils (Cromack and others 1979; Page-Dumroese and others, these proceedings). The use of prescribed burns could greatly increase such soil N losses (Little and Klock 1985; Little and Ohmann 1988; Macadam 1987; Wells and others 1979). Nitrogen is required for tree growth in greater amounts than any other mineral nutrient, and is usually the nutrient most limiting in western forest soils (Edmonds and others 1989). Nitrogen is unique among the soil nutrients because it is present almost entirely in organic forms. No inorganic soil reserve is normally present to alleviate losses of N due to natural or human-caused factors (Wollum and Davey 1975).

Replacement of soil N lost due to forest management practices or wildfire in the Inland Northwest can come from four sources: (1) N present in precipitation and dry deposition, (2) biological N fixation by microorganisms living in plant roots (symbiotic N fixation), (3) N fixation by free-living soil microorganisms (nonsymbiotic N fixation), and (4) N fertilizers. The contribution of each will vary depending on forest age and vegetation type, site location, and management practices. Rainfall can add in excess of 20 kg/ha/yr to sites influenced by industrialized areas, but amounts normally average between 0.5 and 2 kg N/ha/yr in the Inland Northwest (Clayton and Kennedy 1985; Fahey and others 1988; Tiedemann and others 1978). Although some N fertilization trials have been conducted in this region (for example, Graham and Tonn 1985; Shafii and others 1989), widespread fertilizer applications are not presently considered economically feasible.

Symbiotic N fixation has the potential to add significant amounts of N to forest soils of the Inland Northwest. Nitrogen-fixing plants are amenable to manipulation by forest managers and could be considered when developing silvicultural prescriptions, especially those emphasizing forest biodiversity. However, as will be shown, many N-fixing plants are quite site specific, and can cause considerable problems for conifer regeneration. Nonsymbiotic N fixation rates in forest soils are quite low, but this N source is likely critical on sites where N-fixing plants are lacking.

SYMBIOTIC NITROGEN FIXATION

Nitrogen-fixing plants found in forests of the Inland Northwest are grouped into two categories: (1) plants in the family Leguminosae—nine genera, and (2) nonleguminous plants—five genera from four different families (table 1). The distribution patterns of these N-fixing plants generally reflect soil moisture/temperature conditions and stand successional stage. Early seral forests usually have greater shrub and herb development than late seral-climax forests, and would give a different picture of N-fixing plant distribution and importance.

Late Seral-Climax Stands

Legumes are more widely distributed than nonleguminous N-fixing plants in late seral-climax stands throughout the Inland Northwest. Studies in Idaho, Montana, and Wyoming have shown the genus *Lupinus* to be the most common N-fixing plant across all habitat types, while species of *Oxytropis* and *Lotus* were found only in scattered locations (tables 2 and 3). *Shepherdia* was the most frequently occurring nonleguminous N-fixing plant, although *Alnus* and *Purshia* were common in certain habitat types.

Paper presented at the Symposium on Management and Productivity of Western-Montane Forest Soils, Boise, ID, April 10-12, 1990.

Martin F. Jurgensen is Professor of Forest Soils, School of Forestry and Wood Products, Michigan Technological University, Houghton, MI 49931. Jonalea R. Tonn is Forester, Russell T. Graham is Silviculturist, and Alan E. Harvey is Principal Plant Pathologist, Intermountain Research Station, Forest Service, U.S. Department of Agriculture, Moscow, ID 83843. Kathleen Geier-Hayes is Research Forester, Intermountain Research Station, Boise, ID 83702.

Table 1—Nitrogen-fixing plants occurring in Montana, Idaho, and western Wyoming forest habitat types[1]

Nonleguminous plants	
Betulaceae	Rhamnaceae
Alnus incana (L.) Moench	*Ceanothus sanguineus* Pursh
A. rubra Bong.	*C. velutinus* Dougl.
A. sinuata (Regel) Rydb.	
	Rosaceae
Elaeagnaceae	*Cercocarpus ledifolius* Nutt.
Shepherdia canadensis (L.) Nutt.	*Purshia tridentata* (Pursh) DC.
Leguminous plants	
Astragalus adsurgens Hook.	*Lupinus* spp.
A. agrestis Dougl.	*L. argenteus* Pursh
A. alpinus L.	*L. caudatus* Kell.
A. atropubescens Coult. & Fish.	*L. laxiflorus* Dougl.
A. canadensis L.	*L. lepidus* Dougl.
A. drummondii Hook.	*L. leucophyllus* Dougl.
A. kentrophyta Gray	*L. polyphyllus* Lindl.
A. miser Dougl.	*L. sericeus* Pursh
	L. wyethii Wats.
Hedysarum boreale Nutt.	
H. occidentalis Greene	*Oxytropis sericea* Nutt.
H. sulphurescens Rydb.	
	Thermopsis montana Nutt.
Lathyrus bijugatus White	
L. nevadensis Wats.	*Trifolium gymnocarpon* Nutt.
L. ochroleucus Hook.	*T. kingii* Wats.
L. pauciflorus Fern.	*T. latifolium* (Hook.) Greene
	T. longipes Nutt.
Lotus nevadensis (Wats.) Greene	*T. parryi* Gray
	Vicia americana Muhl.

[1]Information from Pfister and others (1977); Steele and others (1981, 1983); Cooper and others (1987).

Purshia was restricted to the drier sites, while *Alnus* was found in cooler, wetter stands. *Ceanothus* showed a scattered distribution in these late seral-climax stands, especially in Idaho. Ponderosa pine (*Pinus ponderosa* Laws.) and Douglas-fir (*Pseudotsuga menziesii* [Beissn.] Franco) sites had the greatest occurrence of N-fixing plants, which likely reflects their more open stand structure.

Although species of at least one nitrogen-fixing plant occurred in all but six of the 115 habitat types examined in Montana, Idaho, and Wyoming, these plants are not major understory components in most older Inland Northwest forests. Even when several N-fixing species are found on the same site, as often happens, the combined effect rarely averages more than 10 percent canopy coverage (Jurgensen and others 1979). However, some genera are so predominant on certain sites they have been designated the understory indicator for the habitat type: *Pinus flexilis/Cercocarpus ledifolius* (PIFL/CELE), *Pinus ponderosa/Purshia tridentata* (PIPO/PUTR), *Pseudotsuga menziesii/Cercocarpus ledifolius* (PSME/CELE), and *Abies lasiocarpa/Alnus sinuata* (ABLA/ALSI).

Early Seral Stands

Much less information is available on the distribution and frequency of N-fixing plants in early seral stands across the region. Most studies have been very site specific and usually detail early successional development after a disturbance, such as timber harvesting or fire. *Ceanothus* has received particular attention since it often becomes abundant after prescribed burns or wildfires. *Ceanothus* seed, which can remain viable in the soil for up to 200 years, requires a heat treatment to break dormancy (Noste and Bushey 1987).

Table 2—Occurrence of nitrogen-fixing plants in forest climax series of Montana[1]

	Climax series							
N-fixing plant	*Pinus flexilis* (24)[2]	*Pinus ponderosa* (81)	*Pseudotsuga* (415)	*Picea* (100)	*Abies grandis* (30)	*Thuja* (42)	*Tsuga* (36)	*Abies lasiocarpa* (682)
	Percent of stands in which genus found							
Nonlegumes								
Alnus	0	0	23	17	17	12	14	15
Ceanothus	0	3	5	0	7	0	0	1
Purshia	4	23	7	0	0	0	0	0
Shepherdia	33	10	23	37	20	10	11	13
Legumes								
Astragalus	54	26	27	3	0	0	0	6
Hedysarum	21	5	6	12	7	0	0	5
Lathyrus	0	0	1	7	0	0	0	1
Lupinus	21	41	35	16	13	5	3	18
Oxytropis	4	4	1	0	0	0	0	0
Trifolium	0	0	1	2	0	0	0	2
Vicia	4	17	3	10	0	2	8	1

[1]Data are from late seral-climax forest stands (Pfister and others 1977).
[2]Total number of stands examined within each habitat series.

Table 3—Occurrence of nitrogen-fixing plants in forest climax series of Idaho and western Wyoming[1]

N-fixing plant	*Pinus flexilis* (34)[2]	*Pinus ponderosa* (99)	*Pseudotsuga* (709)	*Abies grandis* (381)	*Thuja* (269)	*Tsuga heterophylla* (153)	*Picea* (119)	*Tsuga mertensiana* (103)	*Abies lasiocarpa* (963)	*Pinus albicaulis* (53)
	Percent of stands in which genus found									
Nonlegumes										
Alnus	0	0	<1	3	3	1	3	3	3	0
Ceanothus	6	13	14	10	5	2	0	0	1	0
Cercocarpus	9	3	4	0	0	0	0	0	0	0
Purshia	9	36	8	<1	0	0	0	0	<1	6
Shepherdia	9	2	8	2	0	3	34	0	20	23
Legumes										
Astragalus	53	7	14	4	3	0	37	0	8	28
Hedysarum	20	5	2	0	<1	0	10	2	5	7
Lathyrus	0	15	3	11	7	<1	0	0	<1	0
Lotus	0	8	0	0	0	0	0	0	0	0
Lupinus	6	41	17	4	<1	1	3	2	18	23
Oxytropis	8	0	0	0	0	0	0	0	0	2
Thermopsis	0	2	<1	14	10	0	0	2	2	0
Trifolium	0	9	3	6	3	<1	3	0	2	2
Vicia	0	16	4	6	4	0	0	0	<1	0

[1]Data are from late seral and climax forest stands (Cooper and others 1987; Steele and others 1981, 1983).
[2]Total number of stands examined within each habitat series.

Reports of *Ceanothus* canopy coverage on burned sites in Idaho and Montana have ranged from less than 5 percent to over 80 percent (Arno and others 1985; Brown and DeByle 1989; Cholewa and Johnson 1983; Lyon 1971; Mueggler 1965; Noste 1985; Stickney 1980, 1986; Zamora 1975). Generally the hotter and more complete the burn, the greater the development of *Ceanothus* from buried seed (Noste and Bushey 1987; Orme and Leege 1976).

Other N-fixing plants would also be expected to increase after site disturbance, as part of the general increase in understory vegetation. However, few reports are available on the distribution of these plants in young stands of the Inland Northwest. Separate studies in northern Idaho cedar (*Thuja plicata* Donn ex D. Don)-hemlock (*Tsuga heterophylla* [Raf.] Sarg.) habitat types have reported *Alnus* to be either more common or more restricted after burning (Mueggler 1965; Stickney 1986; Wittinger and others 1977). In Montana, Stickney (1980) noted that *Alnus* frequency was reduced on subalpine fir (*Abies lasiocarpa* [Hook.] Nutt.) sites after prescribed burning, but this species is commonly observed on road cuts or other scarified sites (Arno and others 1985). Growth and population density of *Purshia* are generally reduced after prescribed burns and wildfires in the Northern Rocky Mountains (Noste and Bushey 1987; Wagstaff 1980). *Shepherdia* showed a slight reduction in canopy coverage after a prescribed burn in a mixed aspen (*Populus tremuloides* Michx.)-conifer stand in western Wyoming (Brown and DeByle 1989). Both *Purshia* and *Shepherdia* are common mid-seral forest plants in central Idaho habitat types (Steele and Geier-Hayes 1987, 1989).

Little is known about legume distribution after forest disturbance. Some *Lupinus* species are fire survivors that are able to maintain themselves in the initial stages of plant succession after fire. Lyon and Stickney (1976) observed that species of *Lupinus* were abundant after wildfire in southwestern Montana. Canopy coverage of *Lupinus* was little changed after wildfire in a northern Idaho cedar-hemlock stand (Stickney 1986), or following prescribed burns in aspen or mixed aspen-conifer stands of eastern Idaho and northwestern Wyoming (Brown and DeByle 1989). *Astragalus miser* occurred in one of these Wyoming stands prior to burning, and was not present 4 years later. However, *Astragalus canadensis* became abundant following broadcast burning on grand fir (*Abies grandis* [Dougl. ex D. Don] Lindl.) sites in northern Idaho and northeastern Oregon and maintained a sizable population for at least 20 years (Zamora 1975). *Trifolium* was found on disturbed and burned sites in northern Idaho, but showed a rapid decline as the successional plant community developed (Mueggler 1965; Stickney 1986). Two species of *Hedysarum* responded strongly to burning and mechanical site preparation in Douglas-fir and subalpine fir habitat types in western Montana, while *Astragalus* and *Lupinus* did not (Arno and others 1985). Several nitrogen-fixing legumes (*Astragalus*, *Lupinus*, and *Thermopsis*) are important successional components of several central Idaho habitat types (Steele and Geier-Hayes 1987, 1989). The scattered and incomplete nature of these studies indicates that much more information is needed on the successional roles of N-fixing plants in this region.

Nitrogen Additions

Little information is available on the actual contribution of N-fixing plants to the N economy of Inland Northwest forests. The scattered distribution and low numbers of N-fixing plants in most late seral-climax stands suggests that annual N gains on such sites would be small. Fahey and others (1985) estimated that a *Lupinus argenteus* density of 1,000 plants/ha in older, southeastern Wyoming lodgepole pine (*Pinus contorta* Dougl. ex Loud.) stands would add only 0.1 kg N/ha/yr. *Lupinus* growing in Utah aspen stands were reported to fix 0.6 kg N/ha/yr (Skujins and others 1987).

In contrast, much greater amounts of N could be added by N-fixing plants in successional forests. Studies on moist, highly productive sites in western Oregon and Washington have reported additions up to 100 kg of N/ha/yr from *Ceanothus* and *Alnus*, which became established on cut or burned sites (Conard and others 1985; Kimmins and others 1985). Much less information is available on the generally drier sites in the Inland Northwest, but indications are that N gains from N-fixing plants are lower. Youngberg and Wollum (1976) estimated N gains from *Ceanothus velutinus* (70 percent canopy cover) on a clearcut central Oregon ponderosa pine site to be 72 kg N/ha/yr over a 10-year period. A similar 11-year-old stand of *Ceanothus velutinus* (64 percent canopy cover) in northeastern Oregon was reported to fix 32 kg N/ha/yr (McNabb and others 1979). *Lupinus arcticus* (21,600 stems/ha) growing on a cutover lodgepole pine site in southern British Columbia was estimated to fix 2 kg N/ha/yr (Hendrickson and Burgess 1989). *Shepherdia* was also present on this site and added an additional 0.75 kg N/ha/yr.

The presence of N-fixing plants on a site in high numbers does not necessarily mean that significant amounts of N are being fixed. Dalton and Zobel (1977) estimated that less than 0.1 kg N/ha/yr was added to ponderosa and lodgepole pine stands in central Oregon by understories of *Purshia* (20 percent canopy cover). The amount of light reaching the soil surface and soil moisture levels during the growing season are critical factors in determining N-fixing plant activity (Sprent and Sprent 1990).

NONSYMBIOTIC NITROGEN FIXATION

The occurrence of N-fixing plants in most habitat types in the Inland Northwest should not obscure the fact that these plants are lacking or of low frequency on many sites (tables 2 and 3). On these sites, nonsymbiotic N-fixation becomes an important source of N to replace N lost from timber harvesting.

Nonsymbiotic N-fixation rates are strongly related to soil organic matter contents, being much higher in woody residue and surface organic layers than in mineral soil (table 4). Organic matter is required as an energy source for most N-fixing microorganisms (Jurgensen and Davey 1970), and has a high water-holding capacity. However, when these N-fixing rates were multiplied by soil weight/volume ratios to obtain the total amount of N fixed for each soil component, N gains in mineral soil also became important. This was especially evident on a cedar-hemlock site in Idaho, which had mineral soil N-fixation rates 500-600 percent greater than three sites in Montana (table 4). Favorable temperatures and moisture in the fertile northern Idaho ash cap soil encouraged the incorporation of surface organic matter into the mineral soil. Such higher organic matter levels would stimulate the activity of N-fixing bacteria (Granhall and Lindberg 1980).

Nitrogen Gains

The amounts of N fixed by nonsymbiotic N fixation in forest soils of the Inland Northwest generally reflect site productivity (table 4). Of the four old-growth stands examined, the highest N gain was found in a very productive, northern Idaho cedar-hemlock stand, and the lowest in a dry Douglas-fir stand in western Montana. These N-fixation differences were related to amounts of surface organic materials on each site, especially large woody residue (table 5). The greater the woody residue loadings on a site, the greater the N gains. On warm, dry sites, the accumulation of woody residue and other surface organic matter is reduced. Consequently, total N fixation on dry sites is lower than on wetter, more productive sites, while the proportion of N fixed in the mineral soil of these drier sites is greater.

The residue weights for the stands shown in table 4 are higher than regional averages for the Inland Northwest (Jurgensen and others 1987). Therefore, N fixation in woody residue on the majority of sites in this region would likely be lower than the results presented here. However, on many sites with heavy residue loadings, such as in overmature stands on moist sites or after a recent harvest, N gains could be much higher.

The results shown in tables 4 and 5 are from measurements taken during one year—1977. Longer term measurement of soil N-fixation rates has shown considerable annual variation (table 6). These N-fixation differences were related to yearly fluctuations in soil temperature and moisture. The highest N gains were obtained in a

Table 4—Nonsymbiotic nitrogen fixation in old-growth forests

Soil component	Subalpine fir (Montana)		Cedar-hemlock (Montana)		Douglas-fir (Montana)		Cedar-hemlock (Idaho)	
	ng N/d[1]	*g N*[2]	*ng N/d*	*g N*	*ng N/d*	*g N*	*ng N/d*	*g N*
Wood residue	21.0	515	15.6	230	18.6	159	35.2	1,428
Forest floor	32.5	328	15.7	192	12.1	101	14.0	88
Soil wood	26.3	250	7.0	91	9.1	95	19.1	178
Mineral soil	.7	379	.6	326	.6	442	4.0	1,197
Total		1,472		839		797		2,891

[1]Nanograms (10^{-9}) of N fixed/g of soil/day from June-October 1977 as measured by the acetylene reduction technique using a 3:1 ethylene to N conversion ratio.

[2]Total N fixed/ha over a 180-day period. Mineral soil sampled to a depth of 30 cm.

Table 5—Contribution of surface organic materials to soil nonsymbiotic nitrogen fixation in four old-growth forests

Soil component	Subalpine fir (Montana)		Cedar-hemlock (Montana)		Douglas-fir (Montana)		Cedar-hemlock (Idaho)	
	Mg[1]	*% N fix*[2]	*Mg*	*% N fix*	*Mg*	*% N fix*	*Mg*	*% N fix*
Wood residue	145.7	35	83.2	27	45.1	20	154.3	49
Forest floor	36.0	22	49.7	23	26.3	13	23.2	3
Soil wood	35.9	17	50.5	11	37.0	12	47.9	7
Mineral soil	—	26	—	39	—	55	—	41

[1]Dry weight (metric tonnes/ha) of organic material on top of mineral soil.
[2]Percentage of total N fixation shown in table 4.

Table 6—Annual fluctuations in soil nonsymbiotic nitrogen fixation on three old-growth sites in western Montana[1]

Year	Subalpine fir	Cedar-hemlock	Douglas-fir
	g N/ha/180d		
1976	1,246	1,817	1,496
1977	957	609	638
1978	348	309	346
1980	130	209	307
1981	1,097	985	832
Average	756	786	724

[1]Nitrogen fixed in the forest floor, soil wood, and the surface 30 cm of mineral soil as measured by the acetylene reduction technique.

cool, wet year (1976), while the lowest were measured in a warm, dry year (1980). Surprisingly, the average N fixation for these three stands over this 5-year period was quite similar. However, these values do not include N fixation in woody residue.

Many studies have tried to estimate the amounts of nonsymbiotic N fixation in forest soils of different timber types. Values in the literature range from <0.1 to 55 kg N/ha/yr (Boring and others 1988; Dawson 1983; Kimmins and others 1985), but most studies in the Western United States have reported N-fixation rates of <2 kg N/ha/yr (table 7). A direct comparison of these results is difficult due to the different soil layers tested and the various experimental conditions used to measure N fixation. Also, most of these studies were conducted for relatively short times (1 year or less), and as shown in table 6, annual fluctuations in N fixation can be considerable.

Harvesting Impacts

Nonsymbiotic N fixation is especially susceptible to harvesting impacts, since it is dependent on adequate organic matter supplies. The greater the amounts of organic matter removed or destroyed by timber harvesting and site treatments, the greater the possible reduction in N fixation. This effect was studied on a clearcut cedar-hemlock site in northern Idaho that had four harvest/site preparation treatments (table 8). The largest decrease in N fixation (63 percent) occurred after the prescribed burn, which removed 62 percent of the forest floor, soil wood, and woody residue. Slash removal by a bulldozer lowered N fixation by 48 percent, while clearcutting without any site preparation reduced N fixation by only 16 percent. In contrast, N fixation on the heavy residue treatment was 33 percent greater than in the uncut stand. Harvesting and site preparation destroyed much of the forest floor, except on the heavy slash treatment. However, decayed wood in the soil was much less disturbed by logging operations, and became a more important source of N fixation than the forest floor after harvesting. Soil wood is a major organic matter component in many Inland Northwest forest soils and generally retains more moisture than the forest floor during dry summer months (Page-Dumroese and others, these proceedings).

Woody residue was an important source of nonsymbiotic N fixation in the cedar-hemlock stand prior to cutting. Much of this material was removed from the site or destroyed by the prescribed burn and intensive harvesting treatments (table 5). This was especially evident on the tractor-piled treatment, where woody residue loadings were reduced by >90 percent. The low N fixation on both the intensive harvest and burn treatments reflected the low woody residue levels. In contrast, the amount of woody residue remaining after clearcutting was nearly the same as in the uncut stand, but the N fixed was 30 percent less. A similar pattern was seen in the heavy slash treatment, where woody residue loadings were 60 percent higher than in the uncut stand, but N fixation was nearly equal.

The contribution of woody residues to soil N fixation on this site depended on both the amount and type of woody material left after harvest. In the heavy slash treatment 45 percent of the woody residue was in the crumbly or solid rot stage, and 55 percent was undecayed. Solid rot residue is sound enough to withstand fragmentation during logging operations, while crumbly rot residue is easily destroyed (Benson and Schlieter 1980). Decayed wood of both rot types amounted to 59 percent of the total residue on the clearcut treatment. In contrast, 95 percent of the woody residue on the uncut site was large decaying logs, mostly in the crumbly rot stage. Many of these logs were destroyed during harvest and were not present on the cut treatments. They were replaced by smaller pieces of sound wood from harvested trees, which have much lower rates of N fixation (Jurgensen and others 1987).

Table 7—Nonsymbiotic nitrogen fixation in forests of the western United States

Forest type	Location	Source	N fixation	Reference[1]
			kg N/ha/yr	
Douglas-fir				
old growth	Oregon	Woody residue	1.0	1
	Oregon	Woody residue	1.4	2
	Montana	Woody residue, forest floor, mineral soil	0.8	4
various ages	Montana	Woody residue	0 - 1.0	3
23 yr old	Oregon	Forest floor	0.4 - 1.1	5
Subalpine fir				
old growth	Montana	Woody residue	0.7	6
various ages	Montana	Woody residue	0 - 1.7	3
	Montana	Woody residue, forest floor, mineral soil	1.5	4
Cedar-hemlock				
old growth	Idaho	Woody residue, forest floor, mineral soil	2.9	4
	Montana	Woody residue, forest floor, mineral soil	0.8	4
various ages	Idaho	Woody residue	0 - 4.3	3
	Montana	Woody residue	0 - 1.8	3
Mixed conifer				
various ages	Idaho	Living trees	<0.1 - 4.8	7
120 yr old	British Columbia	Woody residue, leaves, bark, forest floor, mineral soil	0.3	8
Lodgepole pine 80 yr old	Wyoming	Woody residue	<0.2	9
Aspen—mature	Utah	Forest floor, mineral soil	0.5	10

[1](1)Sollins and others 1987; (2) Silvester and others 1982; (3) Jurgensen and others 1987; (4) this paper—table 4; (5) Heath and others 1988; (6) Larsen and others 1978; (7) Harvey and others 1989; (8) Cushon and Feller 1989; (9) Fahey and others 1985; (10) Skujins and others 1987.

Table 8—Nonsymbiotic nitrogen fixation on a cedar-hemlock site in northern Idaho after timber harvesting and woody residue removal[1]

Soil component	Residue treatment: None		Prescribed burn		Intensive removal		Heavy residue		Uncut	
	Mg[2]	*gN*[3]	*Mg*	*gN*	*Mg*	*gN*	*Mg*	*gN*	*Mg*	*gN*
Wood residue	146.0	984	57.9	177	10.6	111	249.8	1,483	154.3	1,428
Forest floor	16.7	110	5.5	26	13.3	73	34.5	326	23.2	88
Soil wood	50.9	109	22.4	47	51.6	195	50.3	430	47.9	178
Mineral soil	—	1,218	—	826	—	1,125	—	1,608	—	1,197
Total	213.6	2,421	85.8	1,076	75.5	1,504	334.6	3,847	225.4	2,891

[1]Site was clearcut to a 12.7-cm diameter top. Residue treatments: none—residue left; prescribed burned—broadcast burned in the fall; intensive removal—residue removed by blading with a crawler tractor; heavy residue—residue removed by blading was added to residue left on another area.

[2]Dry weight (metric tonnes/ha) of organic material on top of mineral soil.

[3]Total N fixed/ha over a 180-day period—1977. Mineral soil sampled to a depth of 30 cm.

REPLACEMENT OF NITROGEN LOSSES

While nonsymbiotic N fixation was generally lower after harvesting a northern Idaho cedar-hemlock stand (table 8), the actual reduction was quite small (1-2 kg/ha/yr). The question is whether such small losses in N fixation are important to maintaining long-term site productivity. Using soil organic matter weights before and after harvest (table 8), the N content for these materials (Page-Dumroese and others, these proceedings), and assuming N is lost in proportion to weight losses, 440 kg of N were estimated to have been lost from this cedar-hemlock site by clearcutting and prescribed burning. This does not include any N losses that may have occurred in the mineral soil. Another 200-250 kg N were likely removed from the site in bolewood (Prescott and others 1989). Using an N-fixation gain of 1.08 kg/ha/yr (table 8), and 1.5 kg N/ha/yr added in precipitation, these N losses would be replaced in 250 to 270 years. Such a slow return to original soil N levels could have a considerable impact on subsequent stand growth.

This calculation was based on the assumption that inputs from N fixation will not change as the next stand develops. Nitrogen fixation should increase in the forest floor as this layer increases in thickness during stand development. Nitrogen fixation in the mineral soil was reduced by burning (table 8), but would likely increase as the forest floor becomes thicker. However, these N gains would be at least partially offset by a decrease of N fixation in woody residue. Residue weights would likely decrease with time, as wood decomposition rates are usually greater than residue inputs from young, fast-growing stands. It is only after 100 to 150 years that woody residue begins to increase as mature trees die (Harmon and others 1986; Spies and others 1988). A similar situation would probably occur for the soil wood.

Other sources of nonsymbiotic N fixation not accounted for in these calculations could also add appreciable amounts of N to the soil, and reduce the time required for site recovery. Tree stumps, cull trees left for snags, and large dead roots can add up to 1 kg/ha/yr after harvesting (Granhall and Lindberg 1980; Harvey and others 1989). Increased development of N-fixing algae and lichens on the soil surface after harvest could also add N, but this would likely be small due to generally dry conditions throughout the summer. Nitrogen-fixing bacteria may also be active in the rhizospheres of developing tree seedlings and shrubs (Amaranthus and others 1990).

Nitrogen-fixing plants are present in many cedar-hemlock habitat types in the Inland Northwest (tables 2 and 3). If any of these plants became established on the harvested site, soil N losses could be replaced more rapidly than by nonsymbiotic N fixation alone. Assuming symbiotic N fixation on this cedar-hemlock site could vary from a low of 3 kg N/ha/yr (Hendrickson and Burgess 1989) to a high of 72 kg N/ha/yr (Youngberg and Wollum 1976), the recovery time to preharvest soil N levels would range from 10 to 125 years.

MANAGEMENT IMPLICATIONS

Nitrogen-fixing plants have the potential to add significant amounts of N to forest sites in the Inland Northwest. Of the many N-fixing plants present in this region, *Ceanothus* seems most amenable to management. Fire, as part of postharvest site treatments or stand underburning, would favor *Ceanothus* development in many habitat types. *Alnus*, *Shepherdia*, *Lupinus*, and *Astragalus* also have management possibilities on many sites, but much more information is needed on the response of these genera to stand disturbance in a wide range of habitat types.

While the N added by N-fixing plants could be important in replacing N losses from harvesting or fire, these plants are serious competition for tree seedlings on many sites (McDonald and Fiddler 1989; Petersen and others 1988; Stewart and others 1984). In the short term, reduced stand growth from such plant competiton often far outweighs the benefits from added soil N. Youngberg and Wollum (1976) recommended using *Ceanothus* for soil N enrichment during initial seedling development, followed by herbicide treatment to release the trees. Whether such a chemical treatment would be economically or environmentally possible in the Inland Northwest is questionable. A better alternative would be to create a mosaic of microsite conditions using fire or mechanical scarification, which allows the development of both N-fixing plants and adequate tree regeneration (Geier-Hayes 1987), or to artificially establish N-fixing plants after harvest (Everett and others, these proceedings).

Another option would be to develop silvicultural systems to minimize competing vegetation, but leave as much organic matter on the soil surface as possible. This would favor the activity of nonsymbiotic N-fixing bacteria. While annual N inputs from these bacteria are small, such N gains over the life of the stand can be appreciable. Maintaining soil N levels is critical to continued productivity of Inland Northwest forests. These forests must be managed to minimize N losses from timber harvesting activities, and to encourage N inputs from biological sources.

REFERENCES

Amaranthus, M. P.; Li, C. Y.; Perry, D. A. 1990. Influence of vegetation type and madrone soil inoculum on associative nitrogen fixation in Douglas-fir rhizospheres. Canadian Journal of Forest Research. 20: 368-371.

Arno, S. F.; Simmerman, D. G.; Keane, R. E. 1985. Forest succession on four habitat types in western Montana. Gen. Tech. Rep. INT-177. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 74 p.

Benson, R. E.; Schlieter, J. A. 1980. Logging residues in principal forest types of the Northern Rocky Mountains. Res. Pap. INT-260. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 14 p.

Boring, L. R.; Swank, W. T.; Waide, J. B.; Henderson, G. S. 1988. Sources, fates, and impacts of nitrogen inputs to terrestrial ecosystems: review and synthesis. Biogeochemistry. 6: 119-159.

Brown, J. K.; DeByle, N. V. 1989. Effects of prescribed fire on biomass and plant succession in western aspen. Res. Pap. INT-412. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 16 p.

Cholewa, A. F.; Johnson, F. D. 1983. Secondary succession in the *Pseudotsuga menziesii/Physocarpus malvaceus* association. Northwest Science. 57: 273-282.

Clayton, J. L.; Kennedy, D. A. 1985. Nutrient losses from timber harvest in the Idaho Batholith. Soil Science Society of America Journal. 49: 1041-1049.

Conard, S. G.; Jaramillo, A. E.; Cromack, K., Jr.; Rose, S., compilers. 1985. The role of the genus *Ceanothus* in western forest ecosystems. Gen. Tech. Rep. PNW-182. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 72 p.

Cooper, S. V.; Neiman, K. E.; Steele, R.; David, W. 1987. Forest habitat types of northern Idaho: a second approximation. Gen. Tech. Rep. INT-236. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 135 p.

Cromack, K., Jr.; Swanson, F. J.; Grier, C. C. 1979. A comparison of harvesting methods and their impact on soils and environment in the Pacific Northwest. In: Youngberg, C. T., ed. Forest soils and land use: Proceedings, 5th North American forest soils conference; 1978 August; Fort Collins, CO. Fort Collins, CO: Colorado State University Press: 445-476.

Cushon, G. H.; Feller, M. C. 1989. Asymbiotic nitrogen fixation and denitrification in a mature forest in coastal British Columbia. Canadian Journal of Forest Research. 19: 1194-1200.

Dalton, D. A.; Zobel, D. B. 1977. Ecological aspects of nitrogen fixation by *Purshia tridentata*. Plant and Soil. 48: 57-80.

Dawson, J. O. 1983. Dinitrogen fixation in forest ecosystems. Canadian Journal of Microbiology. 29: 979-992.

Edmonds, R. L.; Binkley, D.; Feller, M. C.; Sollins, P.; Abee, A.; Myrold, D. D. 1989. Nutrient cycling: effects on productivity of northwest forests. In: Perry, D. A.; [and others], eds. Maintaining the long-term productivity of Pacific Northwest forest ecosystems. Portland, OR: Timber Press: 17-35.

Fahey, T. J.; Yavitt, J. B.; Joyce, G. 1988. Precipitation and throughfall chemistry in *Pinus contorta* spp. *latifolia* ecosystems, southeastern Wyoming. Canadian Journal of Forest Research. 18: 337-345.

Fahey, T. J.; Yavitt, J. B.; Pearson, J. A.; Knight, D. H. 1985. The nitrogen cycle in lodgepole pine forest, southeastern Wyoming. Biogeochemistry. 1: 257-275.

Geier-Hayes, K. 1987. Occurrence of conifer seedlings and their microenvironments on disturbed sites in central Idaho. Res. Pap. INT-383. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 12 p.

Graham, R. T.; Tonn, J. R. 1985. Ten-year results of fertilizing grand fir, western hemlock, western larch, and Douglas-fir with nitrogen in northern Idaho. Res. Pap. INT-346. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 6 p.

Granhall, V.; Lindberg, T. 1980. Nitrogen input through biological nitrogen fixation. Ecological Bulletin. 32: 333-342.

Harmon, M. E.; Franklin, J. F.; Swanson, F. J.; Sollins, P.; Gregory, S. V.; Lattin, J. D.; Anderson, N. H.; Cline, S. P.; Aumen, N. G.; Sedell, J. R.; Lienkaemper, G. W.; Cromack, K., Jr.; Cummins, K. W. 1986. Ecology of coarse wood debris in temperate ecosystems. Advances in Ecological Research. 15: 133-302.

Harvey, A. E.; Larsen, M. J.; Jurgensen, M. F.; Jones, E. A. 1989. Nitrogenase activity associated with decayed wood in living northern Idaho conifers. Mycologia. 81: 765-771.

Heath, B.; Sollins, P.; Perry, D. A.; Cromack, K., Jr. 1988. Asymbiotic nitrogen fixation in litter from Pacific Northwest forests. Canadian Journal of Forest Research. 18: 68-74.

Hendrickson, O. Q.; Burgess, D. 1989. Nitrogen-fixing plants in a cut-over lodgepole pine stand of southern British Columbia. Canadian Journal of Forest Research. 19: 936-939.

Jurgensen, M. F.; Davey, C. B. 1970. Nonsymbiotic nitrogen-fixing micro-organisms in acid soils and the rhizosphere. Soils and Fertilizer. 33: 435-446.

Jurgensen, M. F.; Arno, S. F.; Harvey, A. E.; Larsen, M. J.; Pfister, R. D. 1979. Symbiotic and nonsymbiotic nitrogen fixation in Northern Rocky Mountain forest ecosystems. In: Gordon, J. C.; Wheeler, C. T.; Perry, D. A., eds. Symbiotic nitrogen fixation in the management of temperate forests: Proceedings; 1978 April; Corvallis, OR. Corvallis, OR: Oregon State University: 294-308.

Jurgensen, M. F.; Larsen, M. J.; Graham, R. T.; Harvey, A. E. 1987. Nitrogen fixation in woody residue of northern Rocky Mountain conifer forests. Canadian Journal of Forest Research. 17: 1283-1288.

Kimmins, J. P.; Binkley, D.; Chatarpaul, L.; de Catanzaro, J. 1985. Biogeochemistry of temperate forest ecosystems: literature on inventories and dynamics of biomass and nutrients. Inf. Rep. PI-X-47E/F. Chalk River, ON: Petawawa National Forestry Institute. 227 p.

Larsen, M. J.; Jurgensen, M. F.; Harvey, A. E. 1978. N_2 fixation associated with wood decayed by some common fungi in western Montana. Canadian Journal of Forest Research. 8: 341-345.

Little, S. N.; Klock, G. O. 1985. The influence of residue removal and prescribed fire on distributions of forest nutrients. Res. Pap. PNW-338. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 12 p.

Little, S. N.; Ohmann, J. L. 1988. Estimating nitrogen lost from forest floor during prescribed fires in Douglas-fir/western hemlock clearcuts. Forest Science. 34: 152-164.

Lyon, L. J. 1971. Vegetal development following prescribed burning of Douglas-fir in south-central Idaho. Res. Pap. INT-105. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 30 p.

Lyon, L. J.; Stickney, P. F. 1976. Early vegetal succession following large northern Rocky Mountain wildfires. Proceedings Tall Timbers Fire Ecology Conference. 14: 355-375.

Macadam, A. M. 1987. Effects of broadcast slash burning on fuels and soil chemical properties in the sub-boreal spruce zone of central British Columbia. Canadian Journal of Forest Research. 17: 1577-1584.

McDonald, P. M.; Fiddler, G. O. 1989. Competing vegetation in ponderosa pine plantations: ecology and control.

Gen. Tech. Rep. PSW-113. Berkeley, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station. 26 p.

McNabb, D. H.; Geist, J. M.; Youngberg, C. T. 1979. Nitrogen fixation by *Ceanothus velutinus* in northern Oregon. In: Gordon, J. C.; Wheeler, C. T.; Perry, D. A., eds. Symbiotic nitrogen fixation in the management of temperate forests: Proceedings; 1978 April; Corvallis, OR. Corvallis, OR: Oregon State University: 481-482.

Mueggler, W. F. 1965. Ecology of seral shrub communities in the cedar-hemlock zone of northern Idaho. Ecological Monographs. 35: 165-185.

Noste, N. V. 1985. Influence of fire severity on response of evergreen ceanothus. In: Fire's effects on wildlife habitat—symposium proceedings. Gen. Tech. Rep. INT-186. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station: 91-96.

Noste, N. V.; Bushey, C. L. 1987. Fire effects on important shrubs in dry forest habitat types of western Montana and northern Idaho. Gen. Tech. Rep. INT-239. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 22 p.

Orme, M. L.; Leege, T. A. 1976. Emergence and survival of redstem (*Ceanothus sanguineus*) following prescribed burning. Proceedings Tall Timbers Fire Ecology Conference. 14: 391-420.

Petersen, T. D.; Newton, M.; Zedaker, S. M. 1988. Influence of *Ceanothus velutinus* and associated forbs on the water stress and stemwood production of Douglas-fir. Forest Science. 34: 333-343.

Pfister, R. D.; Kovalchik, B. L.; Arno, S. F.; Presby, R. C. 1977. Forest habitat types of Montana. Gen. Tech. Rep. INT-34. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 174 p.

Prescott, C. E.; Corbin, J. P.; Parkinson, D. 1989. Biomass, productivity, and nutrient-use efficiency of aboveground vegetation in four Rocky Mountain coniferous forests. Canadian Journal of Forest Research. 19: 309-317.

Shafii, B.; Moore, J. A.; Olson, J. R. 1989. Effects of nitrogen fertilization on growth of grand fir and Douglas-fir stands in northern Idaho. Western Journal of Applied Forestry. 4: 54-57.

Silvester, W. B.; Sollins, P.; Verhoeven, T.; Cline, S. P. 1982. Nitrogen fixation and acetylene reduction in decaying conifer boles: effects of incubation time, aeration, and moisture content. Canadian Journal of Forest Research. 12: 646-652.

Skujins, J.; Tann, C. C.; Borjesson, I. 1987. Dinitrogen fixation in a montane forest sere determined by $15N_2$ assimilation and in situ acetylene-reduction methods. Soil Biology and Biochemistry. 19: 465-471.

Sollins, P.; Cline, S. P.; Verhoeven, T.; Sachs, D.; Spycher, G. 1987. Patterns of log decay in old-growth Douglas-fir forests. Canadian Journal of Forest Research. 12: 1585-1595.

Spies, T. A.; Franklin, J. F.; Thomas, T. B. 1988. Coarse woody debris in Douglas-fir forest of western Oregon and Washington. Ecology. 69: 1689-1702.

Sprent, J. I.; Sprent, P. 1990. Nitrogen fixing organisms. New York: Chapman and Hall. 256 p.

Steele, R.; Geier-Hayes, K. 1987. The grand fir/blue huckleberry habitat type in central Idaho: succession and management. Gen. Tech. Rep. INT-228. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 66 p.

Steele, R.; Geier-Hayes, K. 1989. The Douglas-fir/ninebark habitat type in central Idaho: succession and management. Gen. Tech. Rep. INT-252. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 65 p.

Steele, R.; Cooper, S. V.; Ondov, D. M.; Roberts, D. W.; Pfister, R. D. 1983. Forest habitat types of eastern Idaho-western Wyoming. Gen. Tech. Rep. INT-144. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 122 p.

Steele, R.; Pfister, R. D.; Ryker, R. A.; Kittams, J. A. 1981. Forest habitat types of central Idaho. Gen. Tech. Rep. INT-114. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 138 p.

Stewart, R. E.; Gross, L. L.; Honkala, B. H. 1984. Effects of competing vegetation on forest trees: a bibliography with abstracts. Gen. Tech. Rep. WO-43. Washington, DC: U.S. Department of Agriculture, Forest Service. [n.p.]

Stickney, P. F. 1980. Data base for post-fire succession, first 6 to 9 years, in Montana larch-fir forests. Gen. Tech. Rep. INT-62. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 133 p.

Stickney, P. F. 1986. First decade plant succession following the Sundance Fire, northern Idaho. Gen. Tech. Rep. INT-197. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 26 p.

Tiedemann, A. R.; Helvey, J. D.; Anderson, T. D. 1978. Stream chemistry and watershed nutrient economy following wildfire and fertilization in eastern Washington. Journal of Environmental Quality. 7: 580-588.

Wagstaff, F. J. 1980. Impact of the 1975 Wallsburg fire on antelope bitterbrush (*Purshia tridentata*). Great Basin Naturalist. 40: 299-302.

Wells, C. G.; Campbell, R. E.; DeBano, L. F.; Lewis, C. E.; Fredrickson, R. L.; Franklin, E. C.; Froelich, R. C.; Dunn, P. H. 1979. Effects of fire on soil: a state-of-knowledge review. Gen. Tech. Rep. WO-7. Washington, DC: U.S. Department of Agriculture, Forest Service. 34 p.

Wittenger, W. T.; Pengelly, W. L.; Irwin, L. L.; Peek, J. M. 1977. A 20-year record of shrub succession in logged areas in the cedar-hemlock zone of northern Idaho. Northwest Science. 51: 161-171.

Wollum, A. G., II; Davey, C. B. 1975. Nitrogen accumulation, transformation and transport in forest soils. In: Bernier, B.; Winget, C. A., eds. Forest soils and forest land management: Proceedings of the Fourth North America forest soils conference; 1974 August; Quebec. Quebec: Laval University Press: 67-106.

Youngberg, C. T.; Wollum, A. G., II. 1976. Nitrogen accretion in developing *Ceanothus velutinus* stands. Soil Science Society of America Journal. 40: 109-112.

Zamora, B. A. 1975. Secondary succession on broadcast-burned clear cuts of the *Abies grandis-Pachistima myrsinites* habitat type in northcentral Idaho. Pullman, WA: Washington State University. 117 p. Thesis.